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14. ABSTRACT

The long term goal of this program is to advance understanding of distributed laser line scan (DLLS) imaging and networking techniques and their applicability to Navy missions which utilize multiple UUVs in support of littoral operations. The planned three year outcome of the work is to provide a validated radiative transfer simulation suite which can allow underwater laser imaging and communications system developers or operators to predict imaging or communication system performance for alternate configurations of bistatic or multistatic UUV based LLS networks under known environmental conditions.

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Final Technical Report: HBOI Underwater Imaging and Communications Research – Phase I

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LONG-TERM GOALS

The long term goal of this program is to advance understanding of distributed laser line scan (DLLS) imaging and networking techniques and their applicability to Navy missions which utilize multiple UUVs in support of littoral operations. The planned three year outcome of the work is to provide a validated radiative transfer simulation suite which can allow underwater laser imaging and communications system developers or operators to predict imaging or communication system performance for alternate configurations of bistatic or multistatic UUV based LLS networks under known environmental conditions.

OBJECTIVES

The effort during the phase I grant has been focused on several objectives:

1) Test tank experimentation with bistatic and multistatic LLS imaging concepts
   The objective was to experimentally investigate the unique performance attributes and channel characteristics of the bistatic and multistatic LLS imaging techniques in specific geometries, examining degradation due to attenuation, volumetric scatter and forward scatter (blur or glow noise) in known scattering suspensions and devising robust image formation and multi-perspective rendering techniques.

2) Development and validation of one-way pulse stretching radiative transfer code
   The objective was to develop and validate time-resolved radiative transfer models that can rapidly and accurately simulate one-way propagation for pulsed laser sources (either narrow collimated or highly divergent beams) in turbid ocean environments under varying degrees of angular pointing misalignment (i.e. off-axis geometries).

3) Forward scattering Mueller Matrix study
   The objective was to develop a detailed understanding of changes in the Mueller Matrix elements in the near-forward (0°-20°) direction with fine angular resolution in various natural and manipulated particle suspensions, from clearer water up to the optical conditions where multiple scattering dominates. This is critical to establish the

potential benefit of using polarization-sensitive receivers for enhancing performance of the techniques under investigation. The radiative transfer tool has also been used to explore the onset of multiple scattering for on and off-axis geometries.

4) Experimental investigations into enabling techniques for multistatic LLS networks
The objective was to investigate techniques that were considered important to facilitate the implementation of collaborating robotic undersea vehicles deploying a multistatic LLS network. The techniques under investigation during this performance period were laser localization using multi-lateration (or hyperbolic positioning) and a non-line-of-sight (NLOS) communications and broadcasting technique.

APPROACH

The approach for meeting these objectives within this funding period involved collaborations with Drs. Tom Giddings and Joe Shirron at Metron Inc. (Reston, VA) for expertise in electro-optic system performance and radiative transfer modeling; Dr Yogesh Agrawal at Sequoia Scientific Inc. (Bellevue, WA) for development of a polarization-sensitive forward-scattering meter; Professor Kenneth Voss at University of Miami (Coral Gables, FL) for measurement of test target BRDF; Dr Frank Caimi (Vero Beach, FL) for optical communications system design and analysis; Dr Charles Mazel at Physical Sciences Inc. (Andover, MA) for independent data and image analysis.

The experimental effort makes use of the large laser test facility within the Ocean Visibility and Optics Laboratory at the Harbor Branch campus of Florida Atlantic University. Imaging and communications system hardware and the custom testing fixtures required to make the experimental measurements are being developed by researchers, engineers and technicians at Harbor Branch under the guidance of Dr Dalgleish.

WORK COMPLETED

Test tank experimentation of bistatic and multistatic LLS imaging concepts
Both bistatic and multistatic (two same-wavelength modulated illuminators, one receiver) imaging measurements have been conducted over extended distances (up to 11 meters target-to-receiver distances) in well-characterized scattering suspensions. Imagery has been acquired and analyzed in both line of sight (LOS) and non line of sight (NLOS) geometries, the latter being when there is no clear path between the target and the receiver. A light field rendering (LFR) approach to bistatic LLS has been experimentally demonstrated, which also enables synthetic aperture imaging (SAI), described in more detail in Ouyang et al., (2011). Automatic scan line synchronization techniques were investigated using real images and a method based on average magnitude difference function (AMDF) pitch detector proved robust even with severely degraded imagery.

Development and validation of one-way pulse stretching radiative transfer code
The models were subjected to a series of validation experiments over 12.5 meter path length in well-characterized scattering suspensions with both on-axis and precisely

manipulated off-axis cases being conducted. More details about the theoretical basis of the model together with validation results can be found in Dalgleish et al., (2010).

Forward scattering Mueller Matrix study

Included in the Monte Carlo model were extra lines of code to track the number of scattering collisions that each simulated photon bundle had experienced on the path to reaching the receiver. This data has been used in exploring the potential benefit of using a polarization analyzer over the receiver, since it is known for some scattering particles that the degree of polarization will decrease as the number of scattering events increases. [1]

A custom LISST-100X has been delivered to provide m11, m12, m21 and m22 over high c values with short path length (0.1 meters). The instrument is useable both *in situ* and in the lab. A salt water testing volume in the light-tight Biophotonics lab at HBOI has been modified to allow longer path length measurements with biological or mineral particles with a newly developed experimental configuration that can allow all 16 Mueller Matrix elements to be acquired simultaneously, Vuorenkoski et al., (2010).

Experimental investigations into enabling techniques for multistatic LLS networks

A prototype laser multi-lateration technique has been implemented based on the knowledge gained in a simulation study. The technique has proven that sub-carrier or coded-pulse phase detection can be used for robust bearing estimation between adjacent illuminators operating over a region of seabed.

A non line-of-sight (NLOS) broadcasting and communication technique has been demonstrated to offer some advantages over conventional LOS communications.

RESULTS

Bistatic LLS Imaging

Bistatic image results are shown in figure 1. The image results from the 2m laser-to-target case show a much more severe contrast degradation and loss of resolution due to volumetric backscatter and laser-to-target forward scatter. At 27 target-to-receiver beam attenuation lengths, the 2m case has almost reached a limit whereas the 0.5m case can still produce a high contrast, low noise image at 33 target-to-receiver beam attenuation lengths. Contrast plots derived from laser pulse time history measurements from both 10% and 99% reflectance Spectralon test panels also show the more rapid contrast reduction with greater laser-to-target distances at high scattering coefficients. To compare with the bistatic LLS results, an intensified CCD camera and powerful lamp combination were also used in the same bistatic geometry to determine the relative performance of this less complex system alternative. These results indicated that even for the 0.25m laser-to-target distance, the Spectralon split target became contrast limited at a c value of $0.75m^{-1}$ (i.e. less than 8 target-to-receiver beam attenuation lengths).

For smaller laser-to-target distances the high quality imagery obtainable indicates that such bistatic or multistatic LLS system architectures would be able to provide images useful for an operator to perform target identification over significant distances in turbid conditions. For example, in turbid coastal conditions ($c=1m^{-1}$) 33 target-to-receiver beam attenuation lengths represents 33m (>100ft) from target to receiver, which could mean from seabed to surface in shallow water operations. However, to fully understand the potential of the bistatic LLS technique in natural waters, it is intended to perform more experiments in natural waters and to develop an accurate time resolved radiative transfer model, which also includes forward scatter glow noise due to laser-to-target beam spreading and pulse stretching for both volumetric scatter and target signals. These are the basis for the ongoing phase II research.

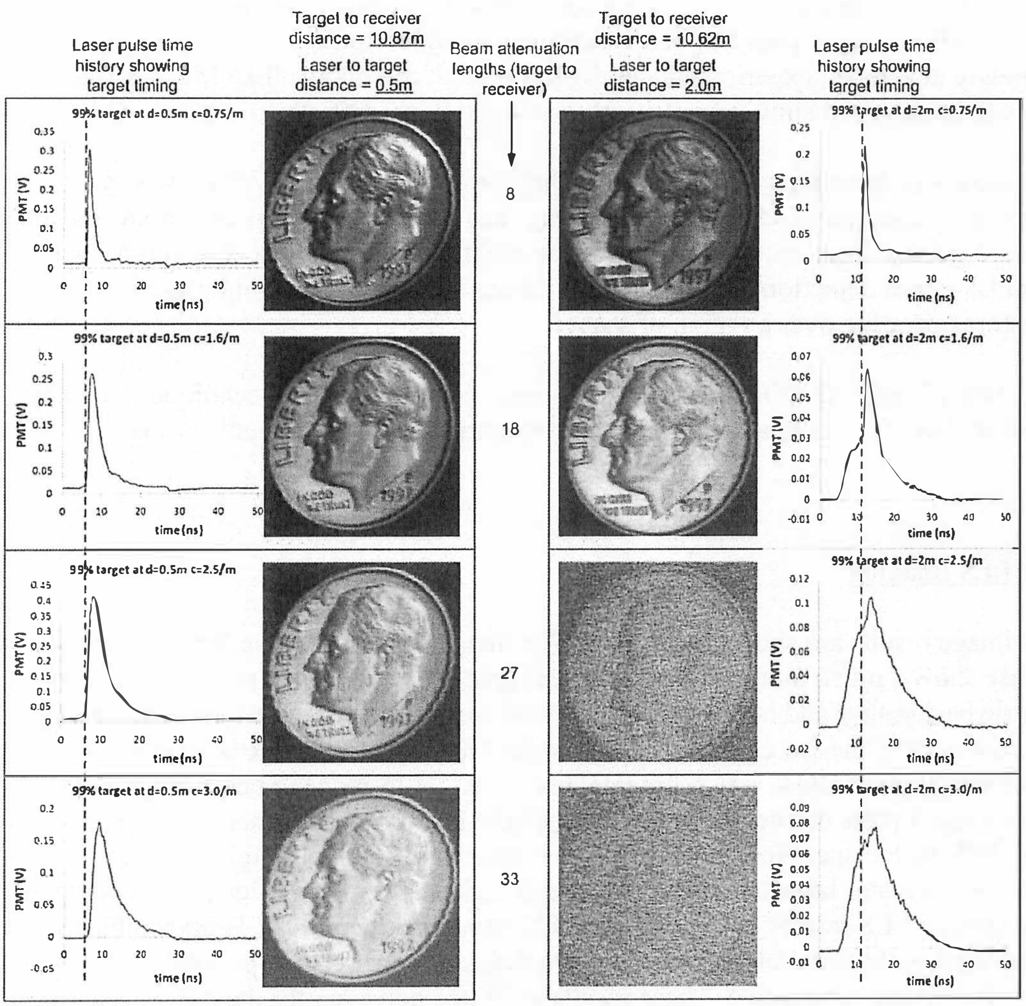

Figure 1. Bistatic LLS extended range (10.62 – 10.87m) image data of dime coin on imaging target at laser-to-target distances of 0.5m (left columns) and 2m (right columns), with CW laser power 130mW as a function of target to receiver beam attenuation lengths.. Laser pulse time history data from near-identical geometrical and environmental conditions is also shown next to each image.

Multistatic LLS Imaging

Distributed Laser Line Scan (DLLS) system concepts have been proven capable of acquiring high quality imagery over large numbers of beam attenuation lengths [2] [3] [4], also exhibiting greater immunity to highly variable optical conditions when compared with the LLS imagers used primarily aboard solitary underwater platforms. Further advantages relate to relatively low laser power, low cost, and simplicity of operational hardware. However, in very turbid conditions, to stay within the optimal operating envelope (i.e. to maintain operational target to receiver distances of tens of meters), distances between illuminator and target need to be no more than a couple of meters. Therefore, the target region from which imagery is obtainable from single imagers is quite small, and long operational times are necessary to cover typical survey areas. For multiple-contact optical identification missions, it is therefore preferred to obtain simultaneous images from multiple small patches of seabed using multiple illuminator-deploying platforms.

A frequency division multiple access (FDMA) communications approach was therefore developed to simultaneously acquire image data from more than one site. Due to the relatively narrow optical transmission spectrum in natural water and a desire to realize low cost and complexity optical and electronic hardware, the possibility of using intensity modulation or coded pulse multiplexing schemes to implement multiple access imaging is attractive using single-wavelength illumination. The hardware selected for these tests were chosen to be compact, with low cost and low power requirement. The target panel was fabricated to include low contrast diffuse 3D shapes, as well as technical targets for contrast, contrast signal noise ratio (CSNR) and image sharpness analysis.

The results summary in figures 2 and 3 demonstrate that at least two separate images can be transmitted simultaneously through more than 20 optical thicknesses with same wavelength, low power (35mW) modulated frame scanned lasers and a miniature photomultiplier tube. When comparing the FDMA to CW results at the modulation frequencies used (104MHz and 124MHz) there are clearly both image bearing signal and volumetric scatter being removed at the RF detection stage.

For the non line of sight data (not shown), where there is no direct path from the target plane to the receiver, the results exhibit some interesting side-effects relating to the rejection of multipath photons which are no longer coherent to the original modulation. A radiative transfer model is under development as part of the phase II effort which will allow for more detailed analysis of the contribution of volumetric scatter and target signal to channel characteristics in alternative system geometries for both LOS and NLOS cases.

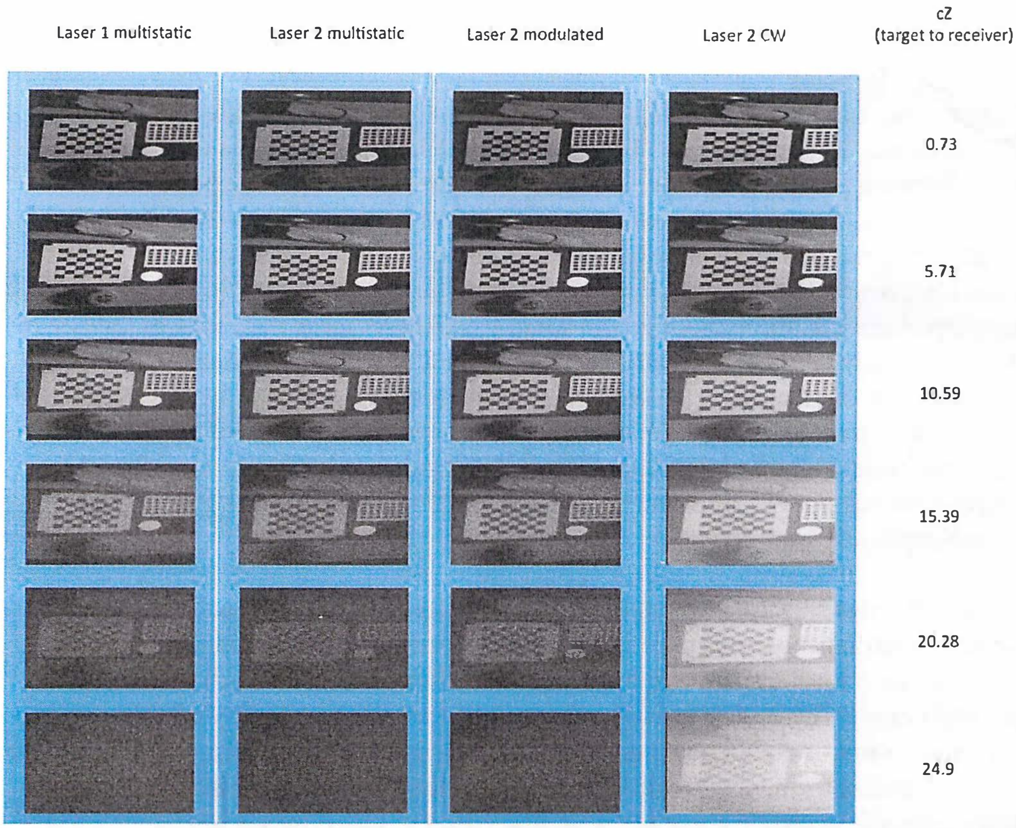

Figure 2: Test tank imaging results for multistatic LLS (columns 1 and 2, 104MHz carrier and 124MHz carrier, respectively), modulated-CW bistatic LLS (column 3, 124MHz carrier) and CW bistatic LLS (column 4). The number of beam attenuation lengths between target and receiver are shown on the right hand side. Average laser power was 35mW for all cases and frame scan period was 2 seconds. The optical receiver was a Hamamatsu 8mm diameter miniature PMT with 50mm diameter f0.83 Lens. The total FOV of the receiver was 9 degrees with flat top response. All images are stretched from min to max. (please note that laser 1 and laser 2 are scanning separate images, albeit with significant overlap)

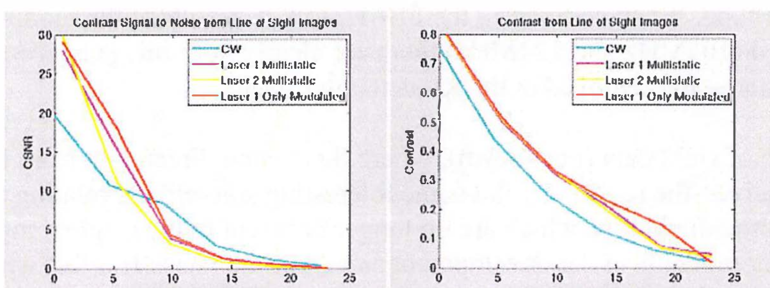

Figure 3: CSNR and contrast image quality metrics for images presented in figure 1.

Synthetic Aperture Imaging

Light Field Rendering (LFR), a type of Image Based Rendering (IBR) technique enables multi-perspective image rendering and visualization without measuring the geometrical dimension of the target. Compared to other IBR techniques, LFR can provide Signal-to-Noise Ratio (SNR) improvement and the ability to image through obscuring objects between the illuminator and target. Another important attribute of LFR is the potential to implement Synthetic Aperture Imaging (SAI) [5] [6]. SAI can be achieved by so-called *dynamically re-parameterized light field* [5]. The results in figure 4 compare raw images with synthetic aperture images generated by LFR. Evidently, demonstrating the capabilities of LFR with video would be more compelling than with static images.

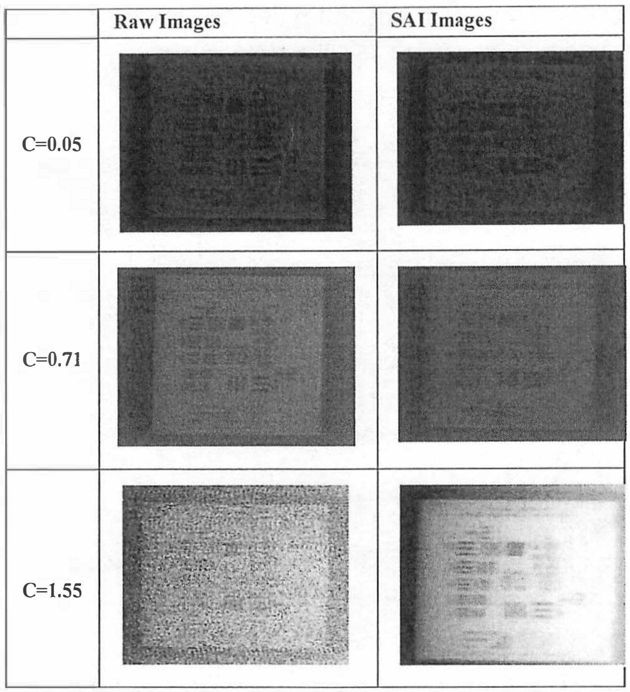

Figure 4: Test tank imaging results for bistatic LLS (column 1), and SAI generated from LFR using a bistatic LLS image matrix (column 2). Laser to target distance was 1.8m. Target to receiver distance was 10.82m.

As can be seen from figure 4, SAI provides a significant image quality improvement at high turbidity. At c=1.55m^{-1}, there is factor of 10 improvement in CSNR for the SAI image. For clear water scenario (c=0.05m^{-1}), there is a slight reduction in CSNR in the SAI case. This is because SAI essentially applies a low pass filter against the input data. Therefore when the raw data noise level is low, SAI image may soften the sharp edges and actually decrease the CSNR. For c=0.71m^{-1}, the CSNR values are almost identical between raw and SAI images, however, the raw image seems more visually appealing due to its sharper edges, even though it is noisier.

<u>Development and validation of one-way pulse stretching radiative transfer code</u>

The Metron Monte Carlo code was subjected to several sets of validation experiments over the funding period. These consisted of acquiring both on and off-axis measurements through the entire length of the tank (12.5m) with a 40uJ green pulsed laser with pulse duration (FWHM) of 500ps. Lab-grade Maalox was used to increase the beam attenuation values from clear water to c=2m^{-1} (i.e. up to 25 beam attenuation lengths), measured by a Wetlabs ac-9 meter with attenuation and absorption being adjusted for scattering error according to Zaneveld [7]. Single scattering albedo was found to be $\approx$ 0.95 throughout. The PMT used was radiometrically calibrated and measured for impulse response to allow for irradiance amplitude and time dispersion comparisons with the simulated data respectively.

Computed peak irradiance results, both simulated and experimentally measured, over the range of turbidities are shown in figure 5.

A summary of the measured versus simulated pulse dispersion, as FWHM pulse width over the range of off-axis displacements is shown in Figure 6.

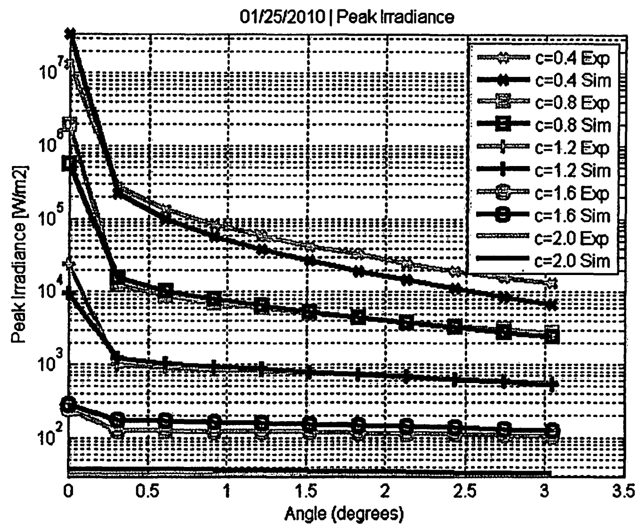

Figure 5: Experimental and simulated comparisons for one-way on and off-axis pulse peak irradiance.

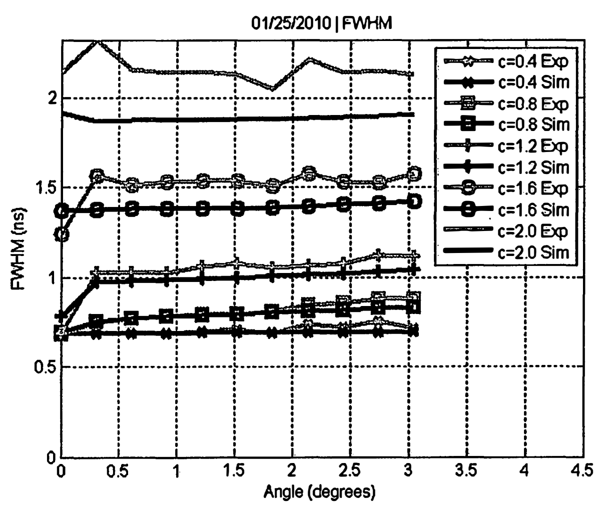

Figure 6. Summary of experimental and simulated comparisons showing FWHM of received dispersed pulses through the full range of angular offsets and turbidities.

The experimental results show some discrepancy with simulations, particularly in the dominant multiple scattering regime. This is believed to be mainly due to the recombination of delayed components of the original pulse that have been reflected from the surface or walls of the test tank. The use of lower albedo particles or additional absorption agent will increase the likelihood that these unnaturally delayed components will be absorbed. Furthermore, it is expected that the use of higher single scatter albedos realistic to natural waters will reduce dispersion due to multiple scatter and therefore improve channel bandwidth, but with the drawback that system performance will become power-limited more rapidly. Discrepancies between simulation and experimentally derived peak irradiance are also believed to result from small errors in detector calibration and underestimation of scattering corrections for attenuation and absorption coefficient with the ac-9 meter. The peak irradiance results are also very sensitive to small errors in measurement of the scattering phase function. These aspects are being investigation during the phase II of the program.

Forward scattering Mueller Matrix study

This work involves studying the effect of higher order forward scattering on one-way channel characteristics. To better understand this phenomenon, the full 16 element Mueller Matrix impulse response of the propagation medium was measured using several different scattering agents and turbidities. By studying the temporal structure of the depolarization of short pulses, the feasibility of more advanced polarization discrimination or diversity schemes is being examined.

Experiments were carried out in the Sea Water Test Tank (SWTT) at HBOI which consists of a 2.18 meters long, 1.52 meters wide and 1.10 meters deep testing volume with optical windows at each end. In the results described herein separate suspensions of magnesium hydroxide and ultra-fine Arizona Test Dust were used as scattering agents and a Wetlabs AC-9 was used to monitor and record the absorption and attenuation coefficients. The polarization optics consist of four Meadowlark Optics Liquid Crystal Variable Retarders (LCVR) with zero retardance compensation, two linear polarizers, a source and a receiver with a remotely controlled motorized neutral density (ND) filter wheel. The transmit optics (in reference to the scattering medium), form a polarization state generator, while the receive optics form a polarization state analyzer. The 16-element Mueller Matrix of the scattering medium is measured by 36 combinations of generator-analyzer states. The source used in the experiments was a 532 nm Q-switched pulsed laser, which produces ~500 ps (FWHM) pulses with ~40 μJ per pulse. The laser was operated at a relatively low (100 Hz) frequency. The receiver was a gated microchannel plate photomultiplier tube (MCP-PMT) manufactured by the Hamamatsu Corporation (R5916U-50).

Two different scattering agents were used during the experiments. The turbidity of the water in the tank was adjusted by adding or removing separate suspensions of a laboratory grade magnesium hydroxide powder and also ultrafine grade Arizona Test Dust (ATD). Both these substances have particle sizes in the range 1-10μm; however magnesium hydroxide is an approximately spherical particle whilst ATD is a random, rough grain.

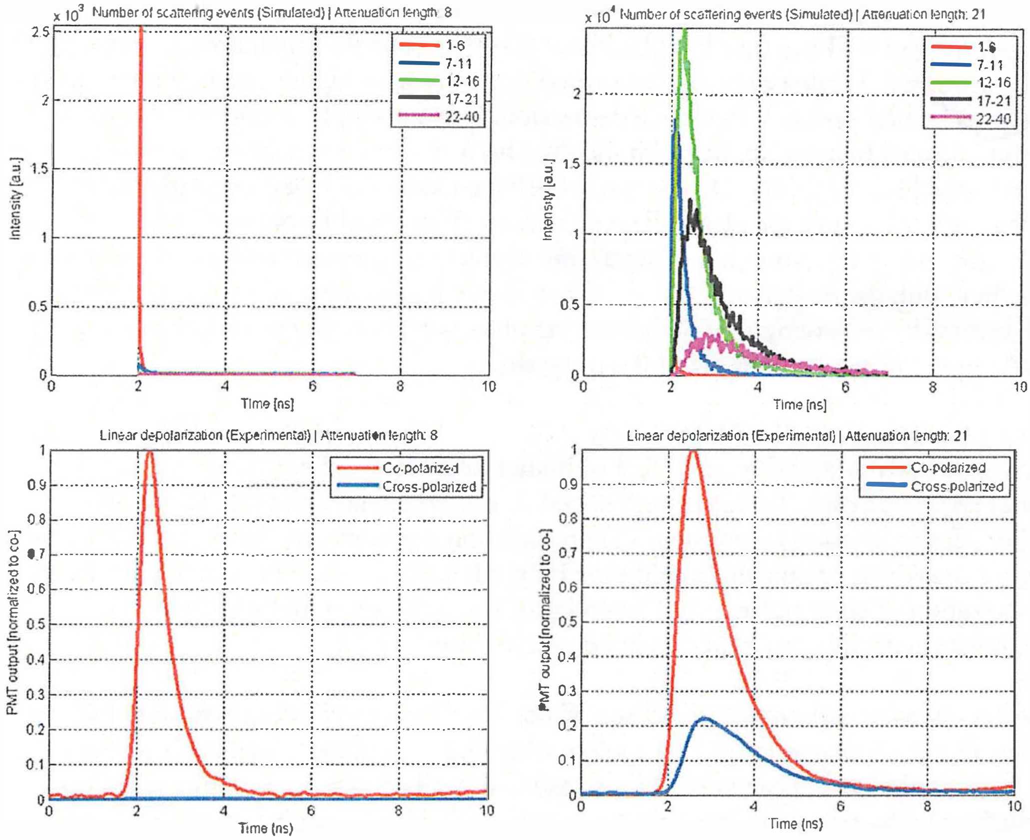

Figure 7: Time histories of both simulated (above) and measured (below) short pulses. The figure pair on the left shows the result from weakly scattering medium and on the right from significantly more turbid medium (magnesium hydroxide).

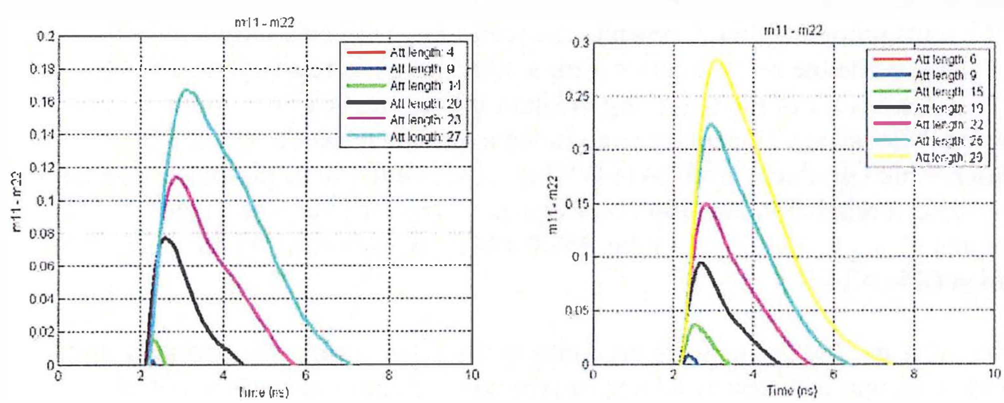

Figure 8: Mueller Matrix elements m11-m22 of the measured pulse at increasing turbidity (magnesium hydroxide left and Arizona Test Dust right).

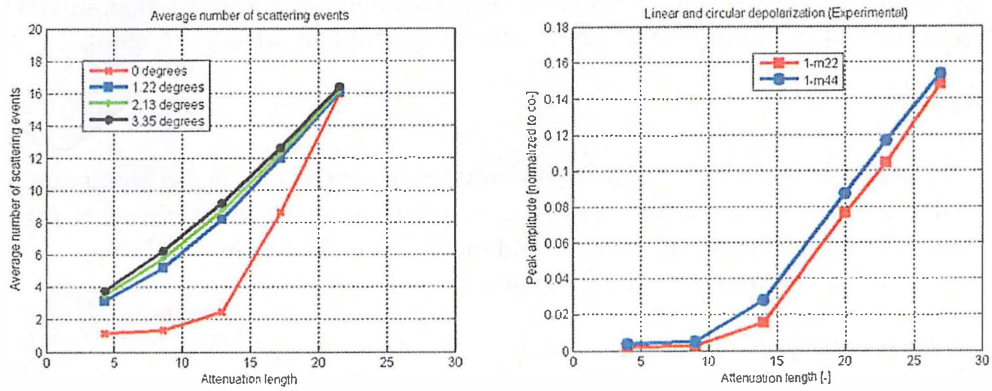

Figure 9: Simulated average number of scattering events (left) and measured Mueller Matrix elements (right) m22 and m44 at increasing turbidity (magnesium hydroxide).

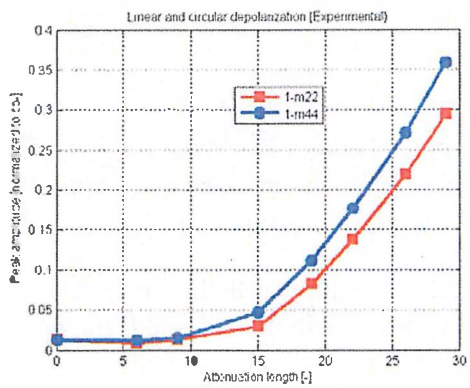

Figure 10: Measured Mueller Matrix elements m22 and m44 at increasing turbidity (Arizona Test Dust).

This study with a newly developed pulsed laser Mueller Matrix measurement prototype and time-resolved radiative transfer code allows for analysis and determination of the relationship between simulated multi-path photons and measured depolarization of short laser pulses. The initial results presented here demonstrate that polarization is gradually lost when turbidity is increased in the forward scattering direction, and also that different particles exhibit different depolarization behaviors. Ongoing experiments are being conducted using a range of other scattering agents, both biological and mineral particles, with optical properties closely matched to those typical of natural waters.

IMPACT/APPLICATIONS

In the long term the multistatic LLS techniques under study, once developed and deployed with swarms of co-operating UUVs may have the potential to provide identification-quality underwater imagery in real-time across much greater regions of seabed than current technology allows.

In the near term, the radiative transfer model being developed under this program could have significant use for the Navy in analyzing potential performance of the multistatic LLS methodology in alternate scenarios. The model, demonstrated image formation and rendering techniques could also be used in the design of optimal platforms, operational schemes and dual purpose imaging/communications system component selection.

TRANSITIONS

The next phase of this program has the specific objectives of packaging the prototype system hardware and environmental characterization sensors in order to conduct at-sea experiments to explore and evaluate system and model performance in a variety of natural waters without the size constraints of the test tank.

RELATED PROJECTS

A Navair SBIR phase II is been performed in collaboration with Advanced Technologies Group (Stuart, FL) to develop a high speed gated Lidar-radar receiver for modulated-pulse LLS underwater imaging.

REFERENCES

[1] Mullen, L. J., Laux, A. and Cochenour, B. “Propagation of modulated light in water: implications for imaging and communications systems”, Appl. Opt. 48, pp. 2607–2612, 2009.

[2] Duntley, S. Q., Austin, R. W., Ensminger, R. L., Petzold, T. J. and Smith, R. C. “Experimental TVI System Report,” Visib. Lab. Tech. Rep., pp. 74–1, 1974.

[3] Dalgleish, F. R., Caimi, F. M., Vuorenkoski, A. K., Britton, W. B. and Ramos, B. “Experiments In Bistatic Laser Line Scan (LLS) Underwater Imaging,” Proc. Marine Technol. Soc./IEEE Oceans Conf., 2009. Paper 090710-001.

[4] Mullen, L. J., Laux, A., Conconour, B. and McBride, W. “Extended Range Underwater Imaging using a Time Varying Intensity (TVI) Approach,” Proc. Marine Technol. Soc./IEEE Oceans Conf., 2009. Paper 090611-005.

[5] Isaksen, A. McMillan, L. and Gortler, S. “Dynamically Reparametrized Light Fields,” in Proc. SIGGRAPH’00, pp. 297–306, 2000.

[6] Vaish, V. Garg, G. Talvala, E. Antunez, E. Wilburn, B. Horowitz, M. and Levoy, M. “Synthetic Aperture Focusing using a Shear-Warp Factorization of the Viewing Transform,” CVPR 2005, 2005.

[7] Zaneveld, J.R.V., Kitchen, J.C. and Moore, C. “The scattering error correction of reflecting-tube absorption meters.” Ocean Optics XII, Proc. SPIE, 2258: 44-55. 1994.

PUBLICATIONS

Dalgleish, F. R. and Caimi. F. M., 2011, "Laser Line Scanners for Undersea Imaging Applications," Book chapter in Handbook of Optical and Laser Scanning (Stutz, G. E. and Marshall, G. F. (Ed.)) CRC Press, Taylor and Francis Group, Boca Raton, FL.

Ouyang, B. Dalgleish, F. R. Vuorenkoski, A.K., Britton, W.B., Ramos B. and Metzger, B., "Visualization for Multi-static Underwater LLS System using Image Based Rendering", IEEE Journal of Oceanic Engineering. 2012. (accepted)

Caimi. F. M. and Dalgleish, F. R. "Performance considerations for continuous-wave and pulsed laser line scan (LLS) imaging systems," Journal of the European Optical Society – Rapid Publications 5, 10020S, 2010.

Dalgleish, F. R. Caimi, F. M., Vuorenkoski, A. K., Britton, W. B. and Ramos. B., 2009 "Experiments in bistatic Laser Line Scan (LLS) underwater imaging". MTS/IEEE Oceans 2009, October 26-30 2009, Biloxi. MI.

Dalgleish F. R., Caimi F. M., Vuorenkoski, A. K., Ramos B., Britton W. B., Giddings T. E., Shirron J. J. and Mazel C. H. "Efficient laser pulse dispersion codes for turbid undersea imaging and communications applications." Proc. SPIE, Vol. 7678, 2010.

Ouyang, B., Dalgleish, F. R., Vuorenkoski, A. K., Britton, W. B., Ramos, B. and Metzger, B. "Visualization for Multi-static Underwater LLS System using Image Based Rendering," Proc. Marine Technol. Soc./IEEE Oceans Conf., 2010.

Vuorenkoski, A. K., Dalgleish, F. R., Metzger, B., Giddings, T. E. and Shirron, J. J. "Multi-path effects on optical communications links," Ocean Optics XX. Sept 27th-Oct 1st 2010. Anchorage, AK.

Ouyang, B. and Dalgleish, F. R., "Underwater Laser Serial Imaging Using Compressive Sensing," Ocean Optics XX. Sept 27th-Oct 1st 2010. Anchorage, AK.

Dalgleish F. R., Ramos, B, Britton, W. B., and Caimi F. M., 2010, "Multistatic distributed laser line scan underwater imaging architecture," Ocean Optics XX. Sept 27th-Oct 1st 2010. Anchorage, AK.

PATENTS

Dalgleish, F.R., Vuorenkoski, A. K. and Ouyang, B. "MEMS Microdisplay Optical Imaging and Sensor Systems for Underwater Scattering Environments." Provisional U.S. Patent Application 61/325,449, 26 March 2010.